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ABSTRACT

Pressure, density, temperature and wind measurements in the upper stratosphere and in the mesosphere resulted from a total of 53 Rocket-Grenade soundings conducted during the period 1960-1965. Most of the soundings were performed over North America (Wallops Island, 38° N and Churchill, 59° N) but some results were also obtained over the tropical Atlantic (Ascension Island, 7° S) and over Northern Europe (Kronogard 66° N). Soundings were carried out simultaneously at these sites and, as part of the COSPAR IQSY effort, were coordinated with soundings measuring similar parameters over other areas of the globe.

Results permit not only a more detailed description of the seasonal and latitudinal variations in the structure and circulation of this region of the atmosphere, but a comparison with IGY measurements reveals that the winter warming of the upper mesosphere over Churchill is

considerably less intense during IQSY than it was during the period of strong solar activity. However, temperatures above 65 km are still substantially warmer in late winter than in summer. Average temperature differences are about 40° K at 80 km. They are very pronounced at midlatitudes (Wallops Island) and become even more extreme at high latitudes where extremely low summer mesopause temperatures were observed. Maximum stratopause temperatures were observed during late winter-early summer. At Wallops Island these maxima of about 280° K coincided with the cessation of the westerly circulation.

The strong westerly flow in winter as well as the easterly flow in summer show two pronounced cores, one just above the stratopause, the other near 75 km. Deviations from the zonal flow indicate the existence of meteorological circulation cells on a synoptic scale with the average meridional flow at Churchill strongly from the north during both summer and winter and at Wallops Island somewhat weaker from the south during the summer. Wind patterns lend credence to the theory that dynamics of the mesosphere is governed by eddy motion, transporting angular momentum across latitude circles.

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CONTENTS

I. Introduction

After the successful exploration of the structure of the upper stratosphere with Rocket Grenade soundings at White Sands, New Mexico, Churchill, Canada and Guam, Mariana Islands, during the International Geophysical Year, (Nordberg and Stroud 1961), we conducted a series of soundings at various latitudes in the Atlantic and North American region during the period of minimum solar activity. Simultaneous, seasonal measurements of temperature, pressure, density and winds were planned at four sites: Point Barrow, Alaska, (71° N); Churchill, Manitoba, Canada, (59° N); Wallops Island, Virginia, (38° N) and Ascension Island, BWI (7° S). Successful soundings were conducted at each of these locations during 1960-1965, however, operational difficulties have limited the number of soundings at the various sites and to date simultaneous observations have been made only at three of the four sites. These took place recently when three successful soundings were conducted each at Pt. Barrow, Wallops Island and Churchill during January and February 1965. Results from this recent series are not completely reduced yet and only preliminary data from the Pt. Barrow soundings were considered in this analysis. The Point Barrow observations are the first known direct measurements of the structure of the mesosphere at this high a latitude. Only four successful acoustic grenade soundings were possible at Ascension Island, two in February and two in August 1964. The August observations were made nearly simultaneously with soundings at Churchill, Wallops Island and at Kronogard, Sweden (66° N). Data from Kronogard, however are as yet, available only for summer 1963 and only preliminary data from the other three sites were considered in this analysis. In addition to the grenade soundings in which temperature, pressure, density, and wind are derived from observations of the soundwaves generated by the exploding rocket-borne grenades, there were three soundings in February and April 1964 at Ascension Island in which pressure, density, and temperature up to 105 km were measured by the Pitot-Static Tube technique. Results of these measurements were reported by Horvath and Simmons (1964) and are included in this analysis.

Acoustic grenade rocket soundings at Churchill resumed in December 1962 after a fire had destroyed the launch facility there in 1960. A total of 15 soundings were carried out during December 1962, February and March 1963, January, February, April and August 1964 and January and February 1965. All but one of these soundings were conducted nearly simultaneously with soundings at Wallops Island. Data from all soundings up to August 1964 were included in this analysis, although the August 1964 data are still of a preliminary nature.

By far the largest number of soundings was obtained at Wallops Island, Virginia since that launch site has been available for the longest period. Forty-two successful soundings took place at Wallops Island between July, 1960 and February, 1965. Soundings took place during every month of the year except October. Results have been analyzed through August 1964.

The times and location of all soundings included in this discussion are summarized in Table I. Lack of space does not permit the presentation here of the complete data from each sounding. However, complete tabulations and graphic presentations of the data for 1960-1963 have been compiled in a report by W. Smith, et al. (1964). A similar report for the complete 1964 data is now in preparation.

Only the basic and salient features of the observations will be summarized here with particular emphasis on their latitudinal and seasonal variations and their relationship to the basic physical processes governing the stratosphere and mesosphere. These results are of interest also because they permit a comparison between the structure of the mesosphere observed during the present period of minimum solar activity and during IGY when solar activity was at its maximum.

Results from the large number of wind observations obtained from Meteorological Network Soundings analyzed by Webb (1964) were also considered to tie in with our observations at the higher altitudes.

Dates and locations of all soundings are summarized in Table I.

II. Discussion of the Observational Results

a. The Temperature Structure—In the stratosphere, temperatures are qualitatively in accord with the solar heating rates expected at the various latitudes and seasons: The highest temperatures are generally observed at high latitudes during summer where maximum heating rates are expected while the lowest temperatures prevail at high latitudes in winter during minimum solar illumination. Quantitatively, however, the observed stratopause temperatures of 255° K near 60° N in winter (Churchill Winter 1962-64 in Figure 1) are about 25° C higher than temperatures calculated by C. Leovy (1964a) for the same latitude and season solely on the basis of heating and cooling rates given by the radiative properties of ozone and carbondioxide. At 60° N in summer (Churchill Summer 1964 in Figure 1) the observed temperatures of 275° K are about 20° C lower than calculated. At high latitudes stratopause temperatures increase by about 25° C from winter to summer, (Figure 2), instead of 70° C calculated from radiative heating and cooling alone. At lower latitudes (Wallops Island) observed temperature excursions are only about 10° C and the seasonal variation of solar heating is also smaller. Figure 1 shows that latitudinal temperature gradients at the mesopause level are much larger in winter than in summer. This is again in good qualitative agreement with radiatively predicted gradients.

The good qualitative agreement between calculated and observed temperatures in the stratosphere at all locations confirms that the absorption of solar radiation by ozone near the 50 km level provides the dominant heat source between the troposphere and the thermosphere. The considerable discrepancy in the magnitude of the seasonal temperature variations in the stratosphere, especially at high latitudes confirms the concept of energy transport from the summer hemisphere to the winter hemisphere by dynamic processes which reduce the theoretically required temperature difference by about a factor of two. Such dynamic processes were postulated by Newell (1963) and Leovy (1964).

A very rapid and large increase in temperature which is apparently not directly related to solar heating occurs during the end of each winter season. (March-May Figure 3.) This warming takes place at 40 km, an altitude somewhat lower than the expected stratopause and considerably earlier than the gradual temperature rise at 50 km induced by solar heating during the period June through August. In fact, many temperature profiles during late winter exhibit their maxima between 40 and 45 km with temperatures equal to or exceeding those reached at 50 km later in the year suggesting the stratopause to be warmest and lowest during spring. This phenomenon is obvious at Wallops because of the large number of observations at that site, but results from

Churchill are insufficient to confirm its existence there (Figure 4). Indications are that the warm upper stratosphere in late winter exists also at relatively low latitudes in the southern hemisphere (Groves 1964). It may be expected that these temperature maxima are dynamically induced and are caused by the final breakdown of the predominantly cyclonic winter circulation which occurs during the same time period. This phenomenon will be considered further in the discussion of the wind observations.

In the lower mesosphere there are practically no seasonal and latitudinal temperature variations in the altitude range of about 60 to 65 km. Indeed, considering the results reported by Groves (1964) for Woomera, Australia (31° S), our earlier IGY data (Nordberg,and Stroud, 1961) and those shown in Figure 1, one may conclude that temperatures at this altitude range generally between 230 and 240° K over the entire globe during all seasons.

The largest seasonal and latitudinal temperature variations take place in the upper mesosphere and at the mesopause. The extreme seasonal excursions of about 70° C at 80 km reported for IGY at Churchill and shown in Figure 2 are considerably smaller in the present results but considerably warmer winter temperatures above 65 are still clearly evident both at Churchill and Wallops Island. Average seasonal temperature excursions at 80 km during the Quiet Sun Year period are about 45° C at Churchill and about 15° C at Wallops Island (Figure 2). It must be concluded that this variation diminishes at low latitudes since no appreciable seasonal variation can be detected in Groves' (1964) results at Woomera and in our (1961) results at White Sands (33° N). At equatorial latitudes for which an average profile is shown in Figure 1, there have not been sufficient soundings yet to positively deduce any absence of seasonal variations. However, the trend demonstrated in the Churchill, Wallops Island, White Sands and Woomera observations and the fact that at all altitudes the average equatorial temperature profile lies between the summer and winter profiles observed at higher latitudes leaves little doubt that at equatorial latitudes the seasonal variations are at a minimum.

The high average lapse rates found during maximum solar heating (high latitude summer), suggest that a very cold upper mesosphere always occurs in conjunction with a warm and high stratopause. The Swedish Grenade soundings made during the summer of 1963 (Witt, et al.) confirm the existence of a warm stratopause (280° K) occuring with a cold mesopause (140° K) at 66° N latitude. On the other hand, during minimum solar heating (high latitude winter), the average lapse rate between 50 and 80 km becomes very small suggesting that a warm upper mesosphere is always found in conjunction with a cold stratopause. Preliminary data from Pt. Barrow, Alaska (71° N) during

January, 1965 (Figure 5) indicate a more nearly isothermal atmosphere from about 40 to 70 km. The seasonal temperature excursions which are of opposite sign in the stratosphere and upper mesosphere (Figure 2) seem to pivot around the level of nearly constant temperature between 60 and 65 km. These observations disagree both qualitatively and quantitatively with temperature distributions computed by Leovy (1964a) based on radiative properties alone. The computations require a much colder mesosphere in winter. Radiative heating and cooling alone requires winter mesopause temperatures of 190° K and summertime temperatures of 230° K at 60° latitude. Observations (Figure 1) show 170° K in summer and 220° K in winter at the same latitude. This discrepancy again necessitates a dynamic mechanism to transport energy on a large scale from the radiatively heated summer stratosphere and mesosphere to the heat deficient winter mesosphere.

Heat sources other than solar radiation have been suggested by Kellogg (1961) who pointed out the possibility of heating the polar upper mesosphere by recombination of atomic oxygen transported downward from the ionosphere and by Maeda (1962) who investigated the possibility of heating by auroral particles. The recent simultaneous observations at Churchill and Wallops Island, however, indicate that the warm upper mesosphere is found at both locations and require an explanation which holds at latitudes outside the polar cap as well as inside.

Figure 1 indicates that the observations made during IGY (Churchill winter 56-58) show considerably higher temperatures than the most recent observations (Churchill winter 62-64), suggesting a relationship between solar activity and high temperatures. This could possibly mean that an auroral heating mechanism exists in addition to the heating evident in the recent data obtained during the period of quiet sun. This possible relationship with solar activity, however, does not necessarily exclude dynamic processes. The mechanism suggested by Newell (1963) whereby eddy motion supplied by disturbances in the zonal mesospheric wind systems provides the energy necessary to counteract the radiative cooling above 60 km could conceivably be enhanced during high solar activity. Differential solar heating which drives the circulation at the stratopause might very well become more intense during increased solar activity thus supplying more kinetic energy to the upper mesosphere which in turn might be available in greater amounts to be transferred to the high winter latitudes. Significantly, summer temperatures throughout mesosphere at Churchill shown in Figure 1 for 1964 are practically the same as those observed during IGY.

b. Pressure Distributions—The average pressure graphs shown in Figure 6 were obtained by integrating the hydrostatic equation for each of the temperature soundings mentioned in Figure 1 and averaging the resulting pressures at each altitude for the appropriate season and location. A measured pressure (usually by balloon sondes), at the lower boundary of each temperature profile was used as the initial value in the integration. The pressure profiles are very useful to demonstrate the relationship between the seasonal and latitudinal temperature variations and the wind patterns described below.

The stratosphere and mesosphere are dominated by a very systematic latitudinal and seasonal pressure variation (Figure 6). These variations are of considerable magnitude throughout the entire region and they converge to zero only at the lower and upper boundaries. Extrapolation of the pressure profiles in Figure 6 to lower altitudes shows that there is a null region in pressure variations in the lower stratosphere near 25 km, a fact which is also known from balloon and Meteorological Rocket Network Soundings. It is evident from the data shown in Figure 6 that another such null region exists near the mesopause. Average pressure profiles for all seasons and latitudes seem to converge toward a common value slightly larger than the U. S. Standard 1962 at 90 km.

In winter, throughout most of the stratosphere and mesosphere, pressures at Churchill are more than 20% lower than at Wallops Island, and close to 30% lower than at equatorial latitudes where the pressure is closest to the standard. The greatest latitudinal pressure gradient in winter occurs near 55 km. The maximum deviation from the standard at all latitudes takes place in winter at Churchill near 65 km.

The variation of the latitudinal pressure gradient with height in winter is plausible on the basis of the temperature profiles. Starting with nearly equal pressure at 25 km in the tropics, at Wallops Island, and at Churchill the much colder winter stratosphere and stratopause at high latitudes causes the pressure to decrease with height more rapidly at high latitudes. In the mesosphere the warmer temperatures at the higher latitudes bring about a smaller pressure decrease with height than at lower latitudes causing the pressure differences finally to disappear at 90 km.

In summer, pressures are higher at Churchill than at Wallops Island at all altitudes but latitudinal pressure gradients are considerably less than in winter. This is because the high latitude summer stratosphere and stratopause are only moderately warmer than their low latitude counterparts. Pressure differences between Wallops Island and Churchill are about one half of the differences observed in winter. Differences between Wallops Island and tropical latitudes are of about equal magnitude during both seasons.

The large seasonal pressure variations of a factor of two between summer and winter at Churchill which were reported during IGY (Nordberg and Stroud, 1961) are still prevalent although with a somewhat diminished amplitude (Factor of 1.8). At the latitude of Wallops Island, the seasonal variation is considerably less and ranges between a factor of 1.15 and 1.2. At equatorial latitudes, soundings have not been made with sufficient continuity to reach a very definite conclusion, but all observations to date indicate that variations in the average pressure are quite small, generally less than the accuracy of the observations which is better than 5%.

c. Wind Patterns—Wind observations in the stratosphere and mesosphere have been more numerous than any other type of observation. The basic features of the general circulation in these regions are, therefore, fairly well understood. A number of publications (Newell, 1963, and Leovy, 1964b) have recently explored these features in greater detail based on our earlier IGY observations and on the large number of meteorological rocket soundings throughout the stratosphere and into the lower mesosphere which have been regularly conducted since 1961. Our observations are summarized in Figures 7 through 12. At lower altitudes, they confirm the features observed by the meteorological network soundings and at higher altitudes they demonstrate a number of systematic patterns which are of relevance to the general circulation picture developed by Newell (1963). All observations confirm basically the existence of the strong cyclonic circulation at all latitudes in winter and a somewhat weaker anticyclonic motion in summer.

Average zonal wind speeds are considerably greater at almost all altitudes at Wallops Island, than at Churchill, both in winter and summer (Figure 7), although occasionally the maximum wind measured at one given altitude in one given sounding at Churchill may exceed the wind speed measured simultaneously at Wallops Island.

At Wallops Island, each year, the winter mesosphere is characterized by two strong westerly maxima at approximately 55 km and 75 km. (Figure 8). There is an indication that the weaker easterlies occurring in summer also form two cores at approximately the same altitudes but they are not as pronounced as the two westerly jets. Observations in the mesosphere at this time have not been made with sufficient continuity to determine the persistence in the reversals of the zonal flow from westerly in winter to easterly in summer and vice versa. However, such studies have been made at lower altitudes by Webb (1964) on the basis of Meteorological Rocket Network Soundings which showed a very consistent pattern in the seasonal reversals. At low and midlatitudes the reversals always occur during mid May and September. Figure 8 shows a consistent slope in the springtime zero isotachs from the upper left to the lower right. It therefore seems to follow that the winter to summer reversal in the lower cores immediately follows the reversals in the upper cores. Sufficient data do not exist for the fall reversals to draw similar conclusions.

In general, the altitude level of maximum average zonal windspeed is higher in summer than in winter. This is consistent with the height of the maximum latitudinal pressure gradient described above. The comparison of the windspeeds between Wallops Island and Churchill also indicates that the steepest latitudinal pressure gradient must occur in the vicinity of 40° N and that this maximum in the gradient is especially pronounced in summer. There is complete consistency for the entire region between the average pressures shown in Figure 6 and the average zonal windspeeds in Figure 7. Maximum winds occur at the heights and seasons where maximum pressure differences are shown and the average zonal windspeed converges toward zero at those altitudes where there is a null region in the pressure variation.

The time cross section of zonal winds at Wallops Island (Figure 8) also shows that the periods of maximum temperature in the upper stratosphere during late winter and early summer (Figure 3) seem to coincide with a decrease in the zonal winds. Indeed during 1961 the maximum temperature occurred exactly when the zonal winds dropped to zero. In 1962, measurements were made in April and June showing temperatures of 270° K during both months. Figure 8 shows that in April the zonal winds had not quite reached zero, yet while in June easterly circulation had already set in. It is reasonable to assume that the actual temperature maximum had occurred during May when the zonal winds were zero. In 1963, temperatures were already very high in March when winds had diminished from their maximum of about 100 m/sec. to about 50 m/sec. No temperature measurements exist during April or May for that year, but one may speculate again that the temperature continued to rise until zonal winds disappeared in May.

There is no evidence of any increase in the meridional wind components (Figure 9) or of any predominance in either the southerly or northerly component during the time of the high late winter temperatures. Zonal circulation is simply absent during these times. Webb (1964) has analyzed the very large number of wind data near the 50 km level resulting from the Meteorological Rocket Network Soundings and has found that except for December, January, and February, the average meridional wind components are very small and show no particular increase in spring.

Webb's analysis also shows that average meridional winds are from the south during the entire year at low and midlatitude stations in the northern hemisphere. Although the meridional flow is not nearly as well organized as the zonal flow, our soundings do show a weak but consistent average component from the south during the winter at all heights up to 70 km at Wallops Island and an equally weak and consistent component from the north at Churchill during both summer and winter (Figure 10). Since these average meridional wind components are much too large to correspond to a true "mean" meridional wind, one may conclude that they must be related to large scale pressure disturbances at these longitudes. The Churchill meridional winds indicate a more or less permanent position of these pressure disturbances.

These pressure disturbances are apparently very deep, reaching well into the mesosphere. They are especially pronounced in winter at the very high latitudes. For example, wind data at Wallops indicate a very strong and steady zonal flow from the west during midwinter (Figures 8 and 9) while at the same time at Churchill the westerly wind component is much weaker and a steady northerly component exists in general (Figures 11 and 12). This is also confirmed by the most recent soundings at Pt. Barrow (Figure 5) suggesting a high pressure cell over the North Pacific and Gulf of Alaska and low pressure over the North Atlantic. This implies that the well known Aleutian Anticyclone may exist up to altitudes of 70 km. A more detailed analysis of one series of simultaneous soundings at Churchill and Wallops Island by Warnecke and Nordberg (1965) supports this speculation. The existence of cyclones and anticyclones throughout the stratosphere and mesosphere supports the theory advanced by Newell (1963) that transient eddy motions are responsible in these regions for the energy transfer from the summer to winter hemisphere, thus bridging the gap between the radiatively required and the actually observed temperature distributions. It seems somewhat surprising, however, that the average meridional wind components at Churchill are from the same direction during both summer and winter, indicating great persistence in the longitudinal position of the pressure cells. Naturally, a much larger number of soundings distributed over a wider range of longitudes would shed some further light on this subject.

The analysis by Warnecke and Nordberg (1965) of a number of the acoustic grenade soundings supplemented by sodium release wind instruments above 70 km showed that the generally accepted circulation patterns cease to exist above about 75 km. Above that altitude the circulation seems to be governed by variations of much smaller time scales than in the stratosphere and mesosphere. Tidal phenomena seem to be of much greater importance at those altitudes than the synoptic scale pressure variations described here for the lower regions.

III. Conclusions

The heated wintertime mesodecline and mesopause observed at Churchill during the IGY is present at both Churchill and Wallops Island during the IQSY, although considerably reduced in magnitude. At 80 km Churchill winter IGY temperatures are 70° C warmer than summer temperatures while during IQSY they are only 45° C warmer than summer. At Wallops Island during IQSY winter temperatures at 80 km are 15° C warmer than summer temperatures. The possibility exists that the less intense winter warming of the upper mesosphere over Churchill during IQSY is associated with the solar cycle. However, the data are insufficient to definitely establish a relationship between temperature and the solar cycle. A sudden increase in temperature not directly related to solar heating takes place at Churchill, Wallops Island and tropical latitudes during the end of the winter season. At this time the stratopause occurs at 40-45 km rather than the normal range of 50-55 km, with temperatures equal to or higher than stratopause temperatures during the summer. The data suggest that the stratopause is warmest and lowest during early spring. This phenomenon is probably related to the breakdown of the polar vortex which occurs at the same time of year.

A region of minimum seasonal and latitudinal temperature variation exists at 60 km, while a similar region exists for pressure at 25 km and 85-90 km. While there are not sufficient data available to draw any definite conclusions about the seasonal variation of temperature and pressure at the tropics, the indications are that these variations are at a minimum, being probably only a few percent over the entire year.

At Wallops Island it appears that there is a temperature maximum in May which coincides with the cessation of the zonal winds. Also at Wallops Island, the winter mesosphere exhibits two pronounced maxima in the westerly winds at 55 km and 75 km. During the summer there appears to be a less pronounced double maxima of easterly winds at the same altitudes.

The persistence of meridional flow from the north at Churchill during the entire year indicates fairly permanent large scale pressure systems in the northern latitudes. Preliminary results from Point Barrow show an average temperature profile with the smallest absolute lapse rate yet observed, 2/3°C per km from 40-70 km. As at Churchill, a steady northerly component exists indicating the existence of a high pressure cell over the North Pacific and Gulf of Alaska, and low pressure over the North Atlantic.

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FIGURE CAPTIONS

Figure 1 - Average 1960-64 summer and winter temperatures for Wallops Island (38° N), 1962-64 winter temperatures for Churchill (59° N), 1964 summer temperatures for Churchill and winter 1964 temperatures for Point Barrow (71° N) are compared to average summer and winter temperatures obtained at Churchill during IGY (1957-58). The IGY Churchill summer temperatures were quite similar to averages from three summer 1964 soundings in Churchill, thus only one profile is shown. An average temperature profile for tropical latitudes obtained in November, 1958 at Guam (13° N) and in February 1964 at Ascension Island (8° S) is shown for comparison. The average profiles are derived from the following number of individual grenade experiment soundings listed in Table I: Wallops winter -17, Wallops summer —10, Churchill winter (IGY) –5, Churchill winter (1962-64) –8, High Latitude summer –8, Low Latitude –6 (Guam) plus 7 (Ascension Island). 1962-64 soundings were conducted nearly simultaneously at Churchill and Wallops.

Figure 2 - Average summer temperatures minus average winter temperatures for Wallops Island (1960-64) and Churchill (1956-58 and 1962-64) as a function of height.

Figure 3 - Variation of temperatures in the stratosphere and mesosphere with altitude and season over Wallops Island (38° N) during 1961-64. Isotherms are based on 34 grenade soundings listed in Table I.

Figure 4 - Variation of temperatures in the stratosphere and mesosphere with altitude and season over Churchill (59° N) during 1962-64. Isotherms are based on 12 grenade soundings listed in Table I.

Figure 5 - 1965 winter stratosphere and mesosphere average temperature and average wind profiles at Point Barrow (preliminary data).

Figure 6 - Seasonal pressure averages as a function of height for Wallops Island (38° N), Churchill (59° N), and equatorial latitudes. Averages are based on the same soundings for which average temperature profiles are shown in Figure 1. Because of their rapid variations with height, observed pressures are shown as deviations from the "U. S. Standard Atmosphere, 1962". Absolute values of standard pressures which apply to the zero percent deviation coordinates are shown in Table II.

Figure 7 - Average zonal wind components vs. altitude for Churchill and Wallops Island. Graphs are based on the same soundings as those shown in Figure 1.

Figure 8 - Variation of zonal wind components with altitude and season over Wallops Island, 1961-64.

Figure 9 - Variation of meridional wind components with altitude and season over Wallops Island, 1961-64.

Figure 10 - Average meridional wind components vs. altitude for Churchill and Wallops Island. Graphs are based on the same soundings as those shown in Figure 1.

Figure 11 - Variation of zonal wind components with altitude and season over Churchill, 1962-64.

Figure 12 - Variation of meridional wind components over Churchill, 1962-64.

TABLE I

DATES, TIMES AND LOCATIONS OF GSFC
METEOROLOGICAL SOUNDING ROCKET EXPERIMENTS
1960-65

Date	Time (GMT)	Location
9 July 1960	0359	Wallops Island
14 February 1961	2350	Wallops Island
17 February 1961	0226	Wallops Island
5 April 1961	1257	Wallops Island
5 May 1961	2300	Wallops Island
6 May 1961	0454	Wallops Island
13 July 1961	2207	Wallops Island
14 July 1961	1602	Wallops Island
20 July 1961	1030	Wallops Island
16 September 1961	2355	Wallops Island
2 March 1962	0001	Wallops Island
2 March 1962	1115	Wallops Island
23 March 1962	2354	Wallops Island
28 March 1962	0004	Wallops Island
18 April 1962	0928	Wallops Island
7 June 1962	0105	Wallops Island
8 June 1962	0153	Wallops Island
1 December 1962	2125	Wallops Island
4 December 1962	0705	Churchill
6 December 1962	0532	Wallops Island

Date	Time (GMT)	Location
6 December 1962	0543	Churchill
20 February 1963	2334	Churchill
20 February 1963	2347	Wallops Island
28 February 1963	2147	Churchill
28 February 1963	2211	Wallops Island
9 March 1963	0001	Wallops Island
9 March 1963	0001	Churchill
7 December 1963	1312	Wallops Island
24 January 1964	0016	Wallops Island
29 January 1964	0411	Wallops Island
29 January 1964	0417	Churchill
29 January 1964	0418	Ascension Island
4 February 1964	0135*	Ascension Island
4 February 1964	0146	Wallops Island
5 February 1964	0040	Churchill
5 February 1964	0320	Wallops Island
13 February 1964	0430	Wallops Island
13 February 1964	0430	Churchill
13 February 1964	0455	Ascension Island
7 March 1964	0245	Wallops Island
15 April 1964	0122*	Ascension Island
15 April 1964	1556*	Ascension Island
18 April 1964	0039	Churchill
18 April 1964	0100	Wallops Island

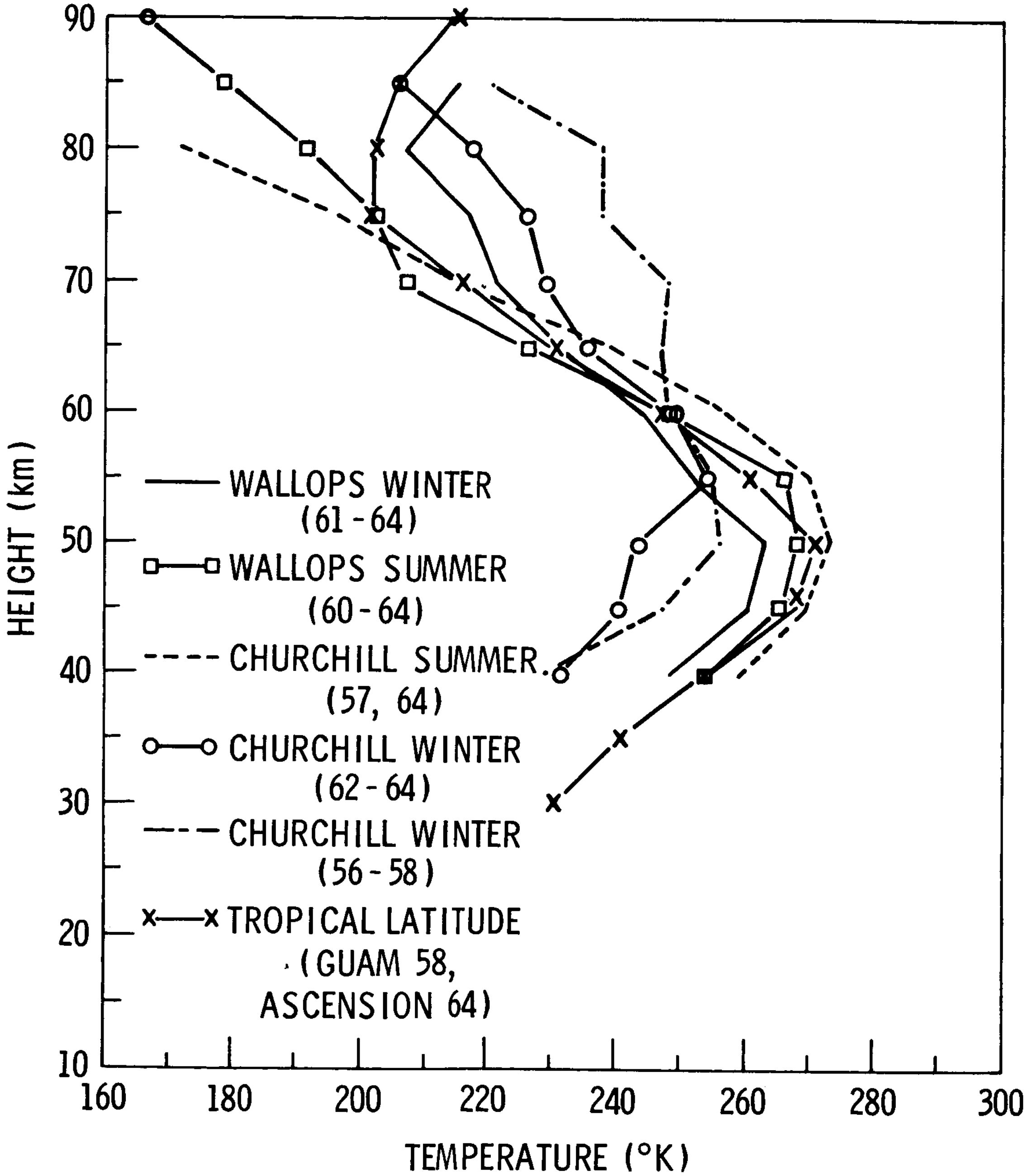
Date	Time (GMT)	Location
7 August 1964	0600	Wallops Island
8 August 1964	1000	Churchill
12 August 1964	0149	Wallops Island
12 August 1964	0215	Churchill
16 August 1964	0315	Wallops Island
16 August 1964	0553	Ascension Island
17 August 1964	1255	Ascension Island
18 August 1964	0115	Churchill
18 August 1964	0125	Wallops Island
27 January 1965	2132	Point Barrow
4 February 1965	0445	Point Barrow
8 February 1965	2215	Point Barrow

All soundings were rocket grenade experiments except the pitot-static experiments which are noted with an asterisk (*).

TABLE II

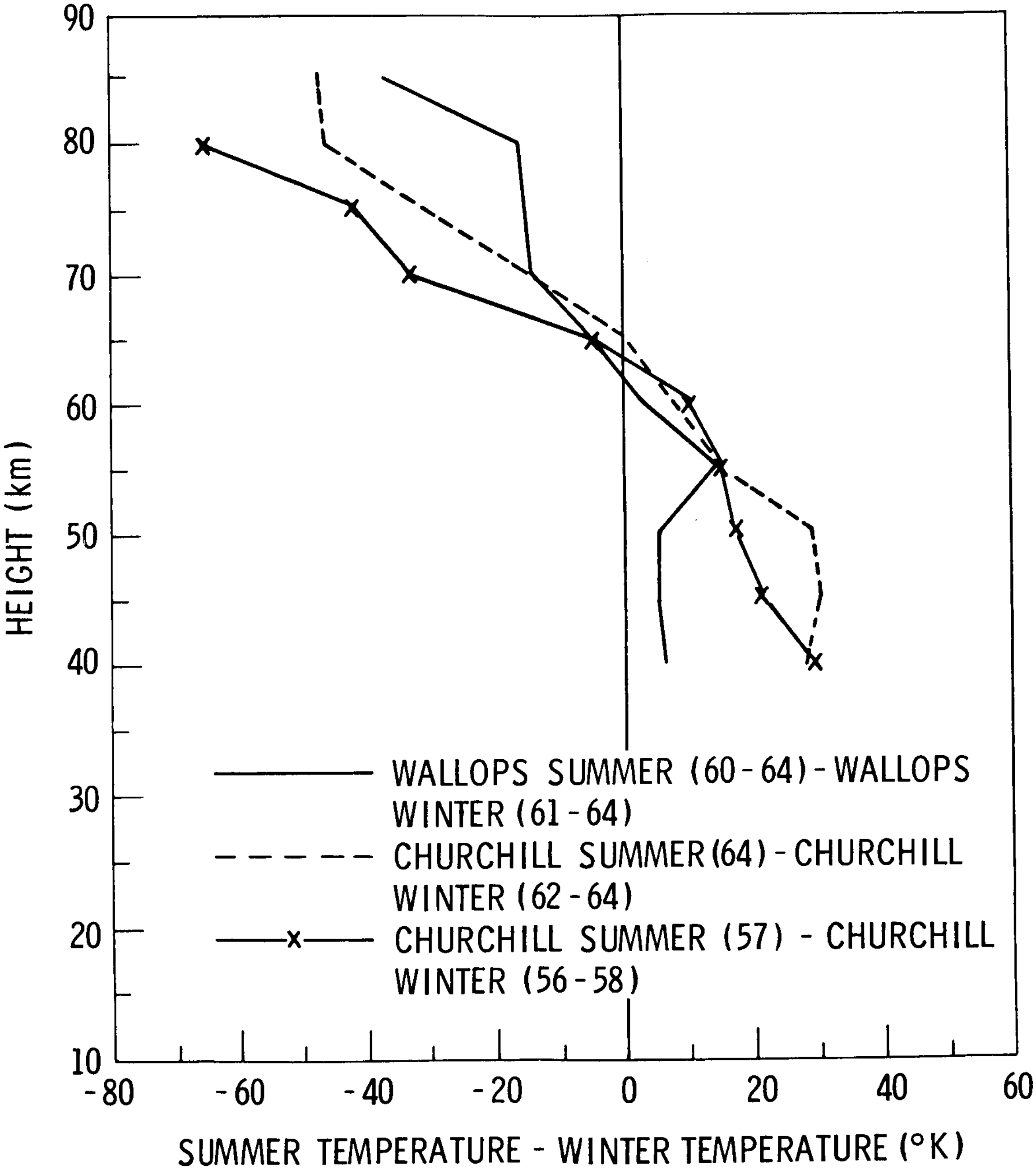
U.S. STANDARD ATMOSPHERE 1962 PRESSURE VS. HEIGHT

Altitude, km	Pressure, N/M^2
30	1197.0
35	431.0
40	287.1
45	149.1
50	79.8
55	42.8
60	22.5
65	11.4
70	5.5
75	2.5
80	1.0
85	0.4
90	0.2



90
80
70
60
50
40
30
20
10
HEIGHT (km)
WALLOPS WINTER
(61 - 64)
WALLOPS SUMMER
(60 - 64)
CHURCHILL SUMMER
(57, 64)
CHURCHILL WINTER
(62 - 64)
CHURCHILL WINTER
(56 - 58)
TROPICAL LATITUDE
(GUAM 58,
ASCENSION 64)
160
180
200
220
240
260
280
300
TEMPERATURE (°K)

Figure 1



90
80
70
60
50
40
30
20
10
HEIGHT (km)
-80
-60
-40
-20
0
20
40
60
SUMMER TEMPERATURE - WINTER TEMPERATURE (°K)
WALLOPS SUMMER (60-64) - WALLOPS WINTER (61-64)
CHURCHILL SUMMER (64) - CHURCHILL WINTER (62-64)
CHURCHILL SUMMER (57) - CHURCHILL WINTER (56-58)

Figure 2

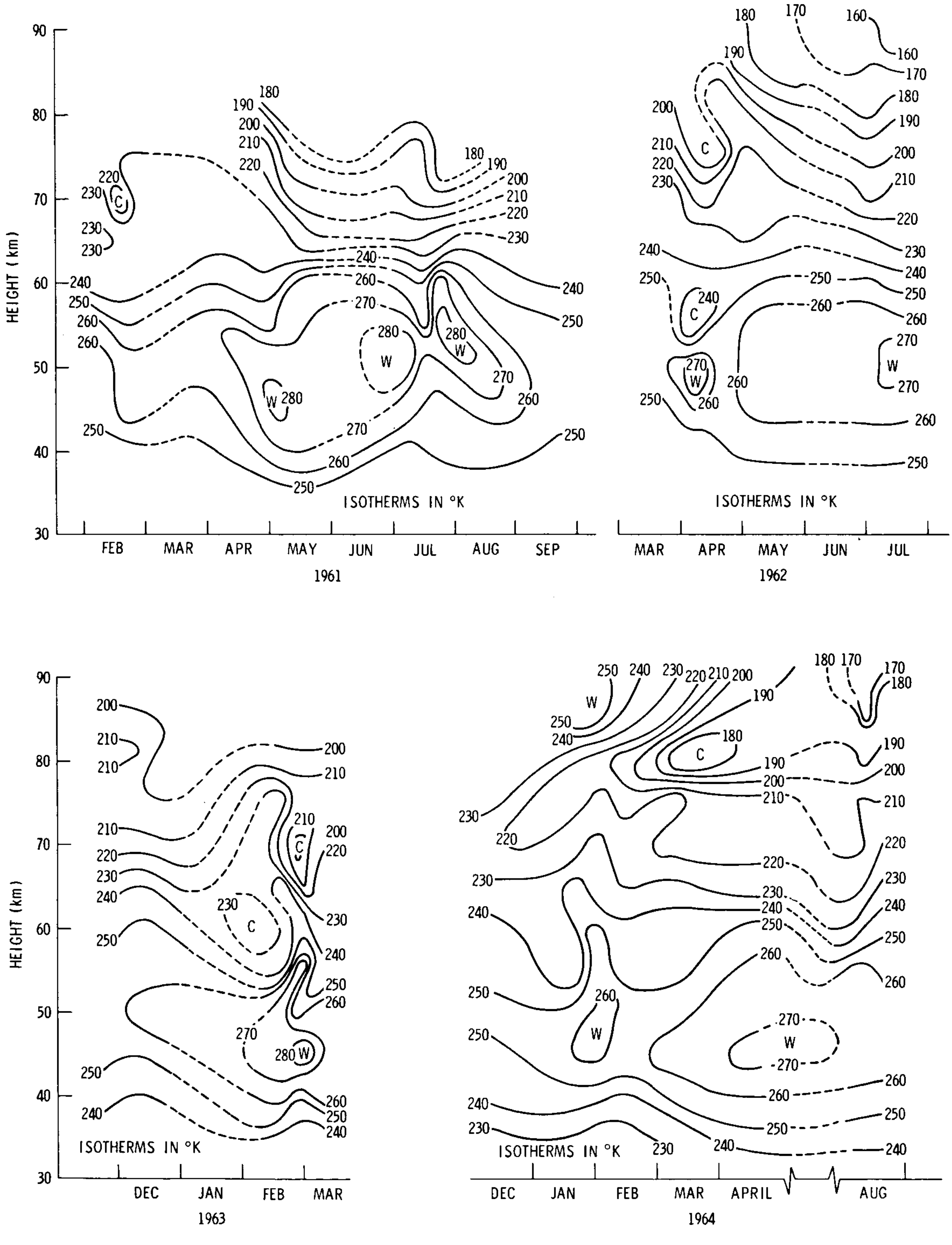

HEIGHT (km)
ISOTHERMS IN °K
FEB MAR APR MAY JUN JUL AUG SEP
1961
ISOTHERMS IN °K
MAR APR MAY JUN JUL
1962
HEIGHT (km)
ISOTHERMS IN °K
DEC JAN FEB MAR
1963
ISOTHERMS IN °K
DEC JAN FEB MAR APRIL AUG
1964

Figure 3

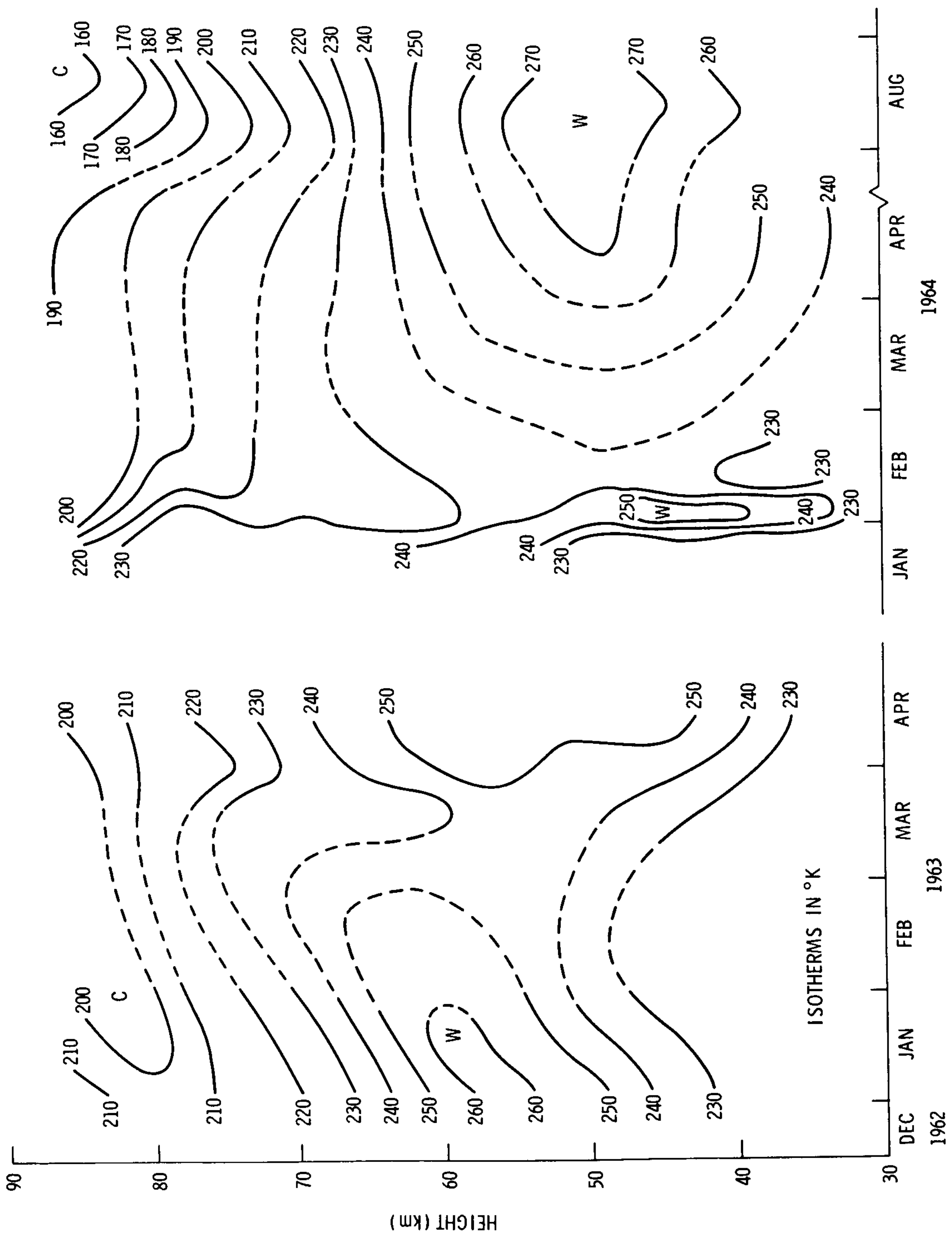

HEIGHT (km)
90
80
70
60
50
40
30
ISOTHERMS IN °K
DEC
1962
JAN
FEB
1963
MAR
APR
JAN
FEB
MAR
1964
APR
AUG
C
W

Figure 4

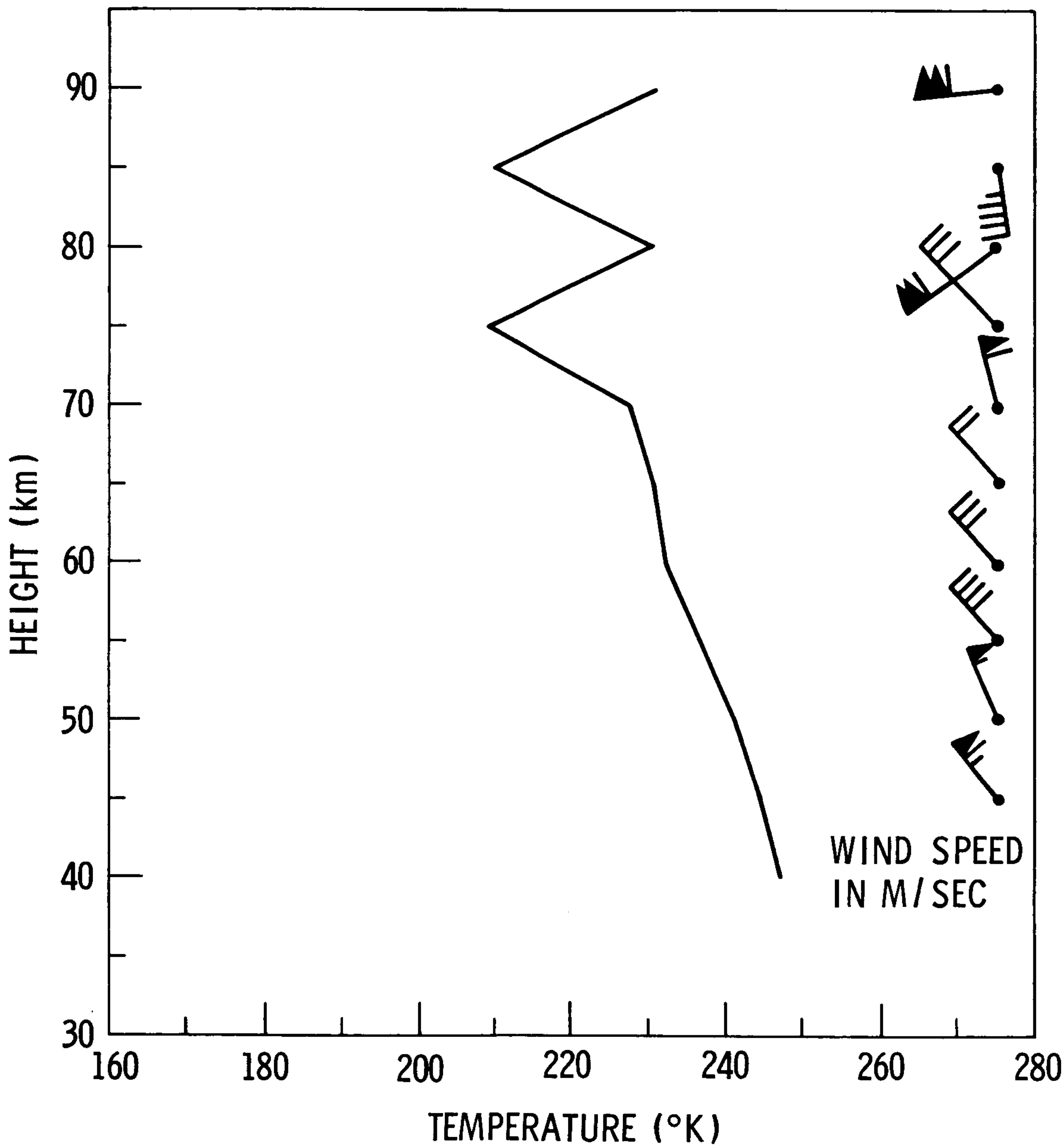
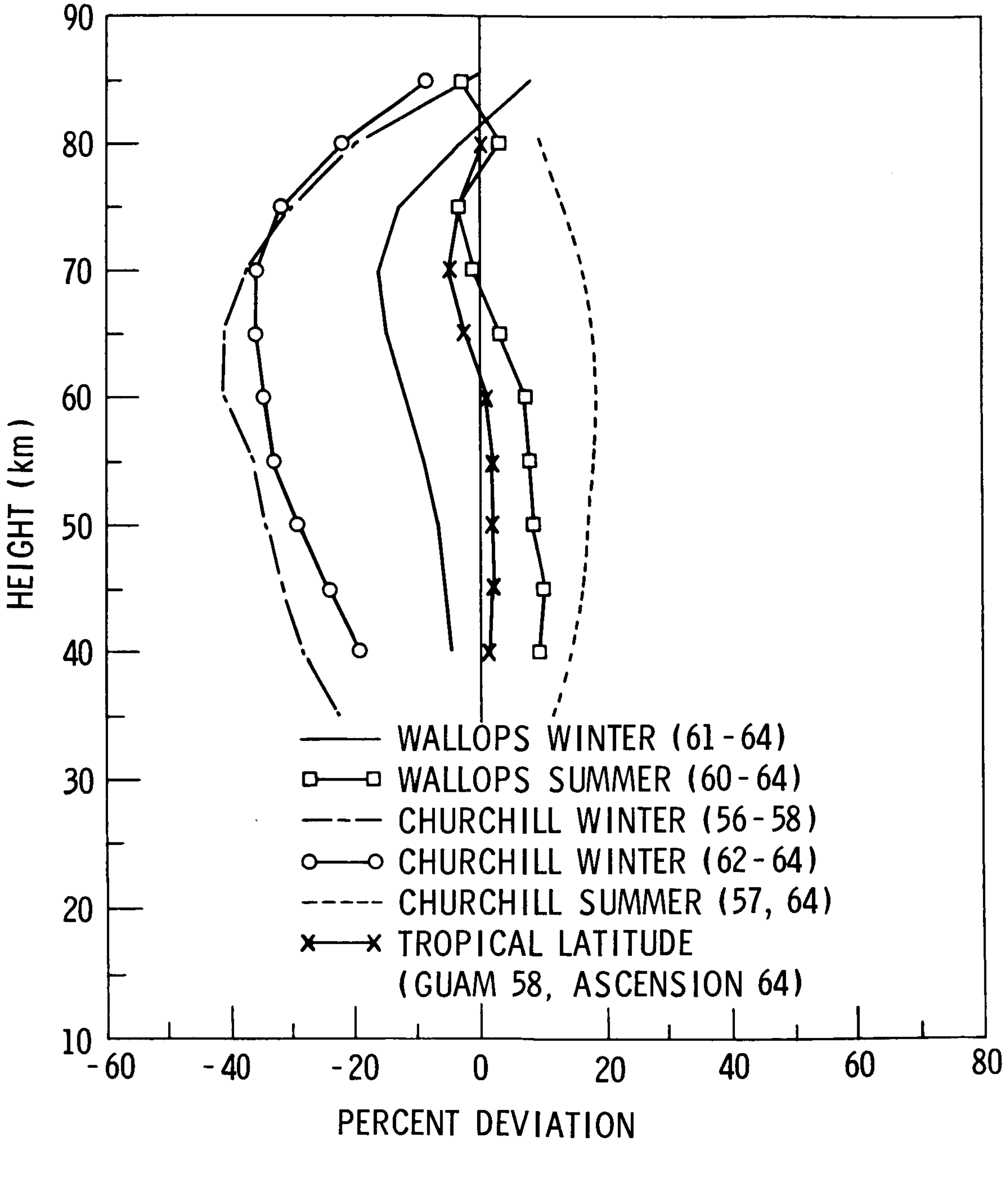

90
80
70
60
50
40
30
HEIGHT (km)
160
180
200
220
240
260
280
TEMPERATURE (°K)
WIND SPEED
IN M/SEC

Figure 5



90
80
70
60
50
40
30
20
10
HEIGHT (km)
WALLOPS WINTER (61-64)
WALLOPS SUMMER (60-64)
CHURCHILL WINTER (56-58)
CHURCHILL WINTER (62-64)
CHURCHILL SUMMER (57, 64)
TROPICAL LATITUDE
(GUAM 58, ASCENSION 64)
-60
-40
-20
0
20
40
60
80
PERCENT DEVIATION

Figure 6

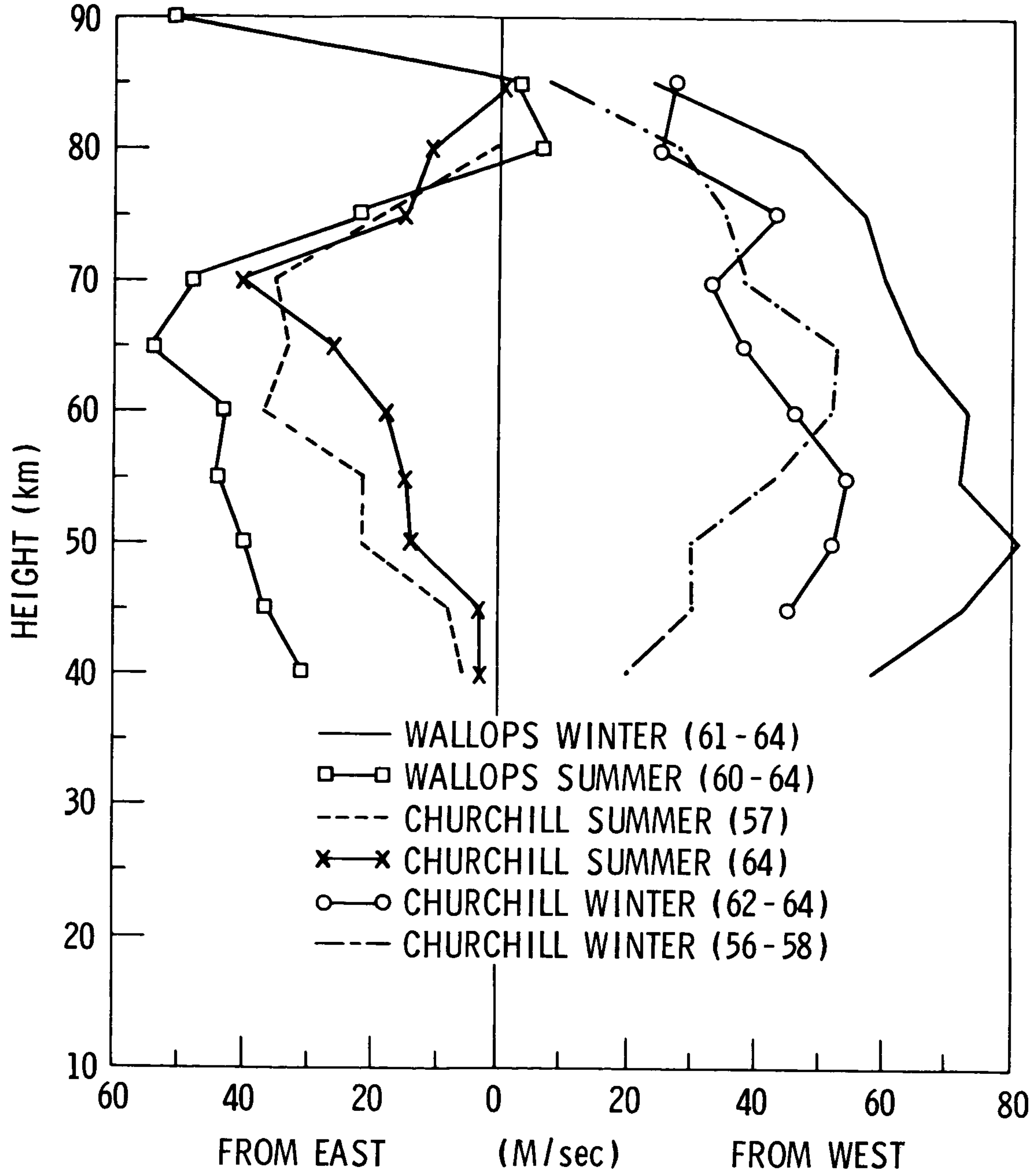

90
80
70
60
50
40
30
20
10
HEIGHT (km)
WALLOPS WINTER (61-64)
WALLOPS SUMMER (60-64)
CHURCHILL SUMMER (57)
CHURCHILL SUMMER (64)
CHURCHILL WINTER (62-64)
CHURCHILL WINTER (56-58)
60
40
20
0
20
40
60
80
FROM EAST
(M/sec)
FROM WEST

Figure 7

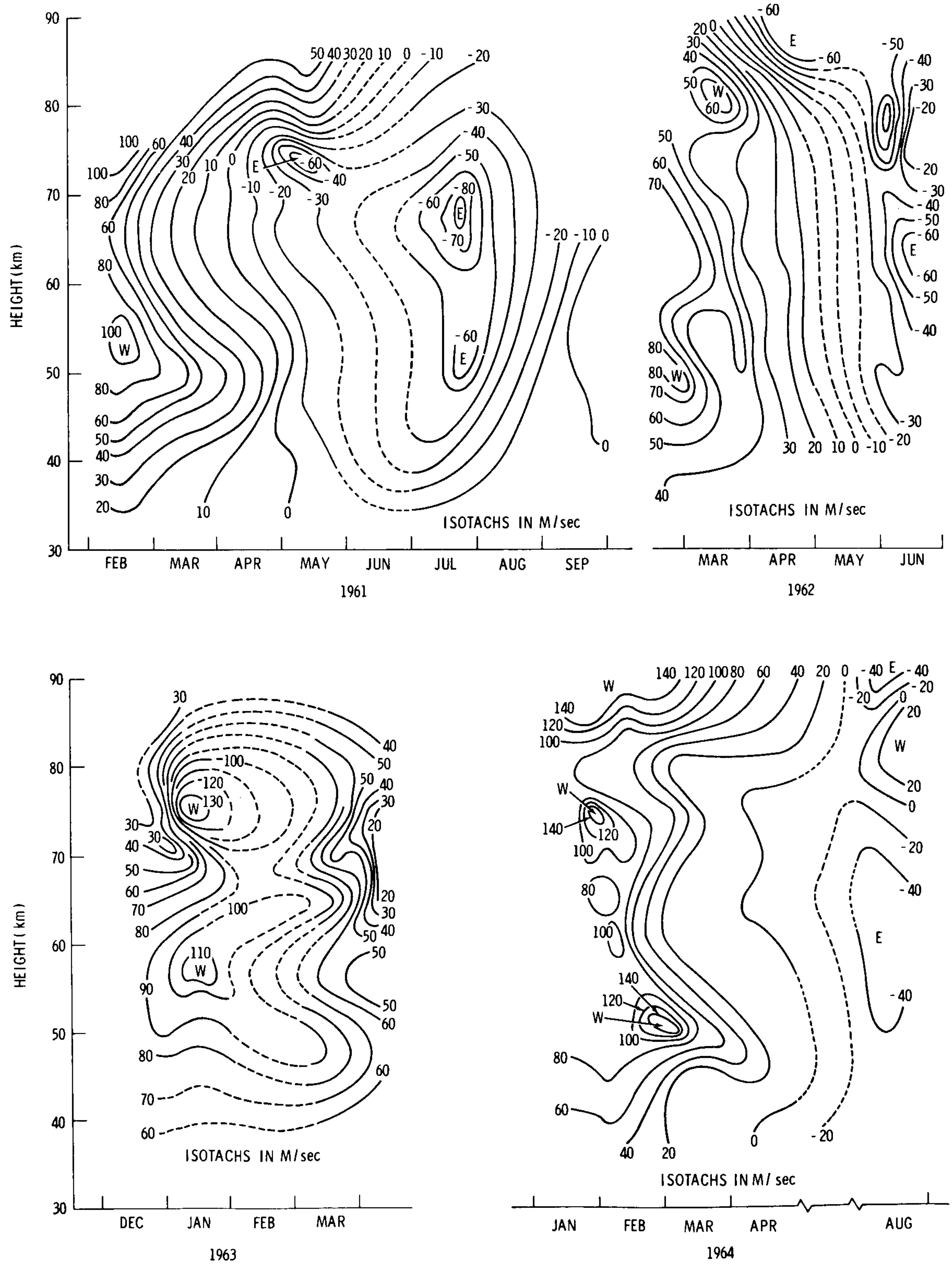

HEIGHT (km)
ISOTACHS IN M/sec
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
1961
MAR
APR
MAY
JUN
1962
HEIGHT (km)
DEC
JAN
FEB
MAR
1963
JAN
FEB
MAR
APR
AUG
1964
W
E

Figure 8

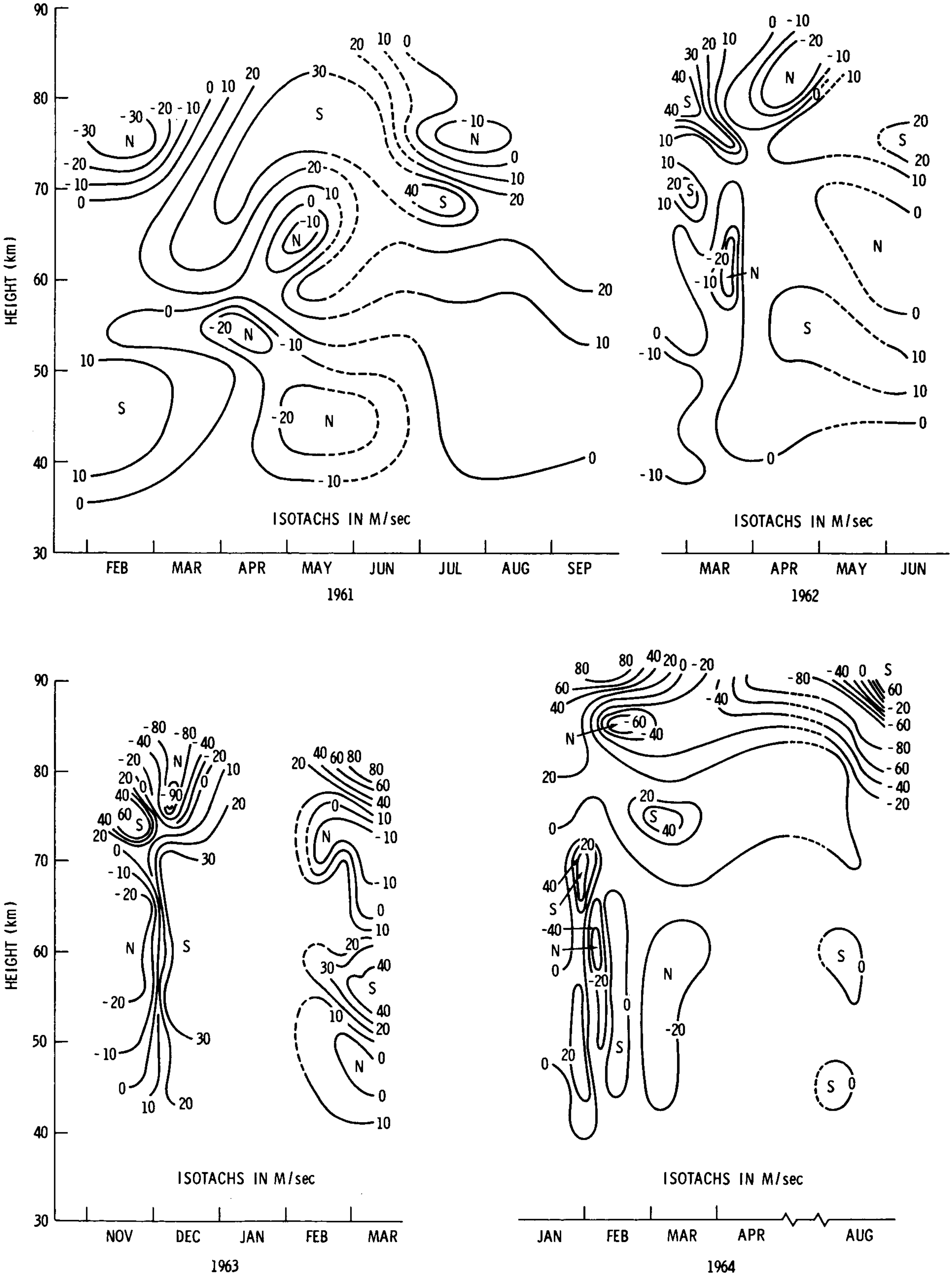

HEIGHT (km)
ISOTACHS IN M/sec
FEB MAR APR MAY JUN JUL AUG SEP
1961
MAR APR MAY JUN
1962
NOV DEC JAN FEB MAR
1963
JAN FEB MAR APR AUG
1964

Figure 9

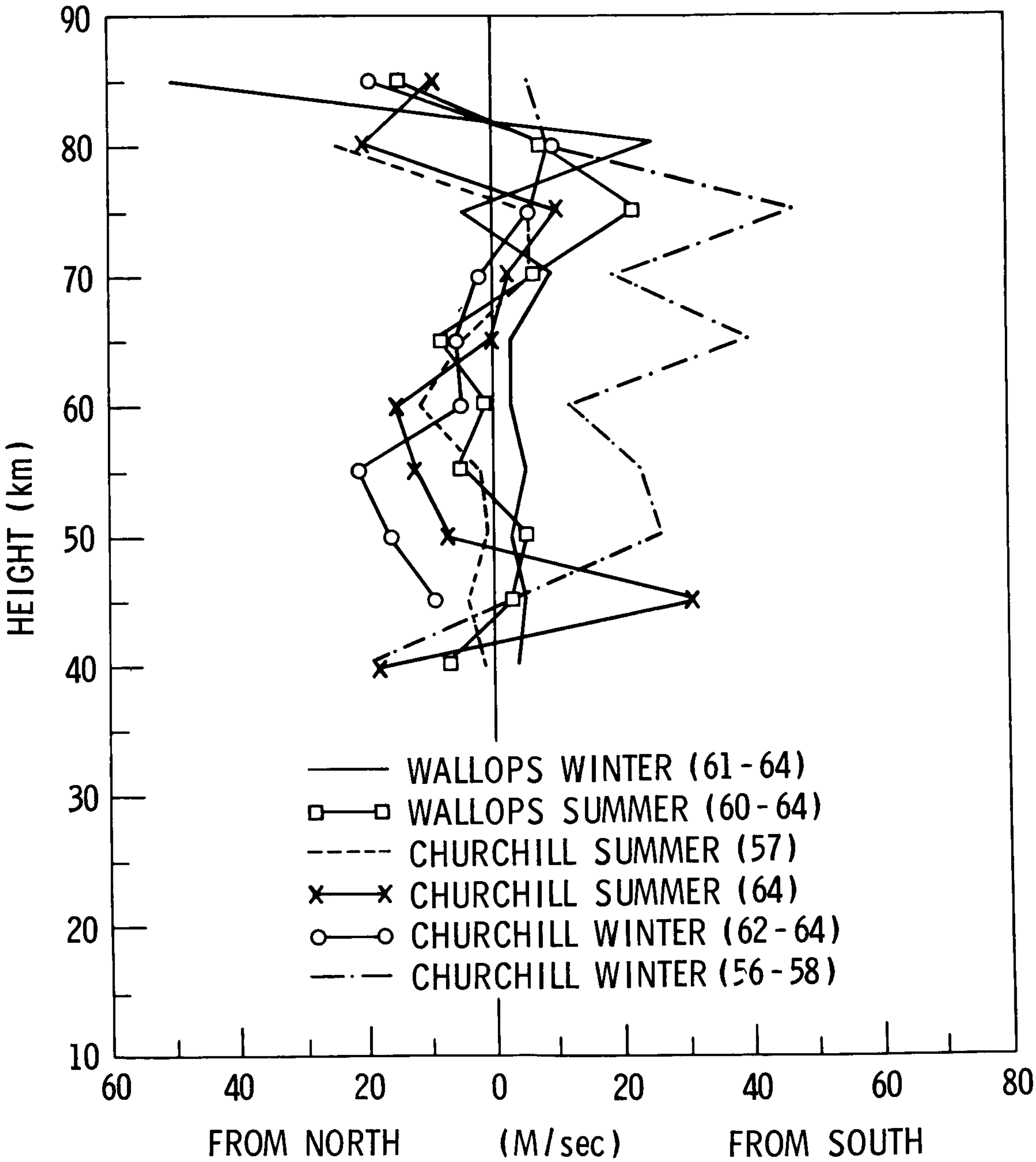

90
80
70
60
50
40
30
20
10
HEIGHT (km)
WALLOPS WINTER (61-64)
WALLOPS SUMMER (60-64)
CHURCHILL SUMMER (57)
CHURCHILL SUMMER (64)
CHURCHILL WINTER (62-64)
CHURCHILL WINTER (56-58)
60
40
20
0
20
40
60
80
FROM NORTH
(M/sec)
FROM SOUTH

Figure 10

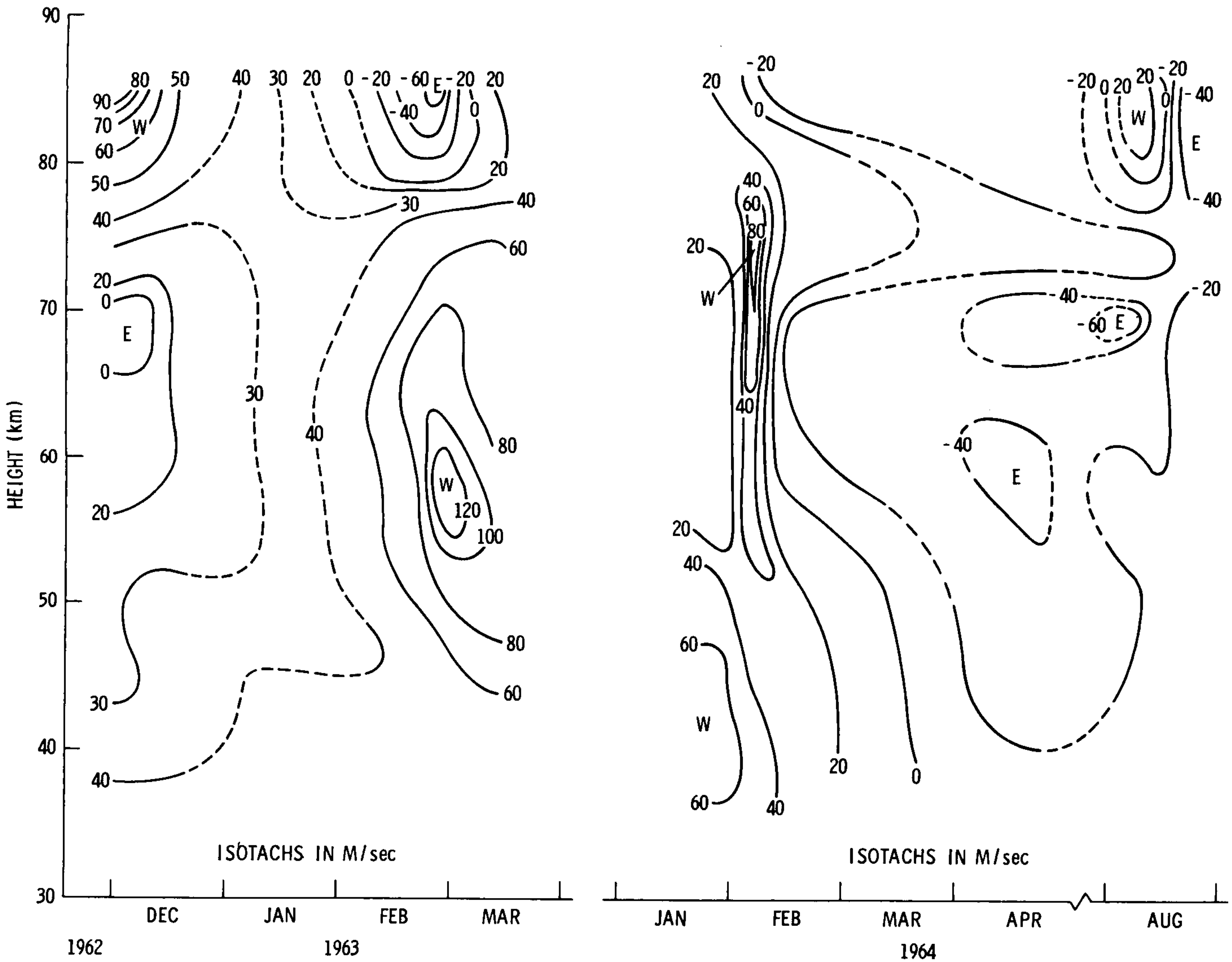
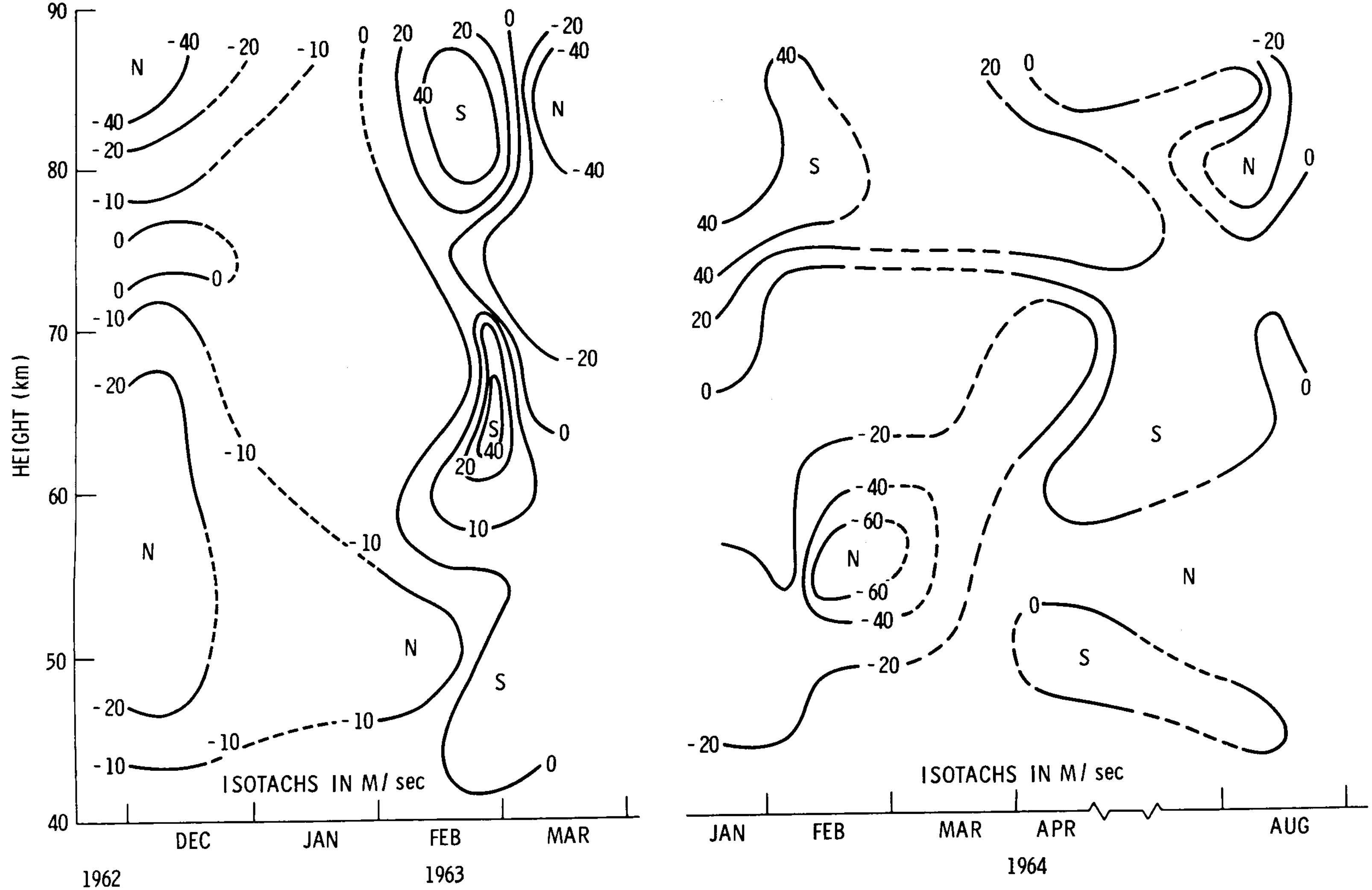

HEIGHT (km)
ISOTACHS IN M/sec
DEC
JAN
FEB
MAR
1962
1963
ISOTACHS IN M/sec
JAN
FEB
MAR
APR
AUG
1964

Figure 11



HEIGHT (km)
90
80
70
60
50
40
ISOTACHS IN M/ sec
DEC
JAN
FEB
MAR
1962
1963
ISOTACHS IN M/ sec
JAN
FEB
MAR
APR
AUG
1964

Figure 12